Dynamics of the vegetation eco-boundary under climate warming in Northeast China

ZOU Chun-jing (邹春静)*, HAN Shi-jie (韩士杰), ZHOU Yu-mei (周玉梅)
ZHANG Jun-hui (张军辉), WANG Chen-rui (王琛瑞)
(*Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110015, P.R. China*)

Abstract: Based on data from 210 meteorological stations in Northeast China and survey on zonal climax vegetation, the Kira's warmth index (W_I), coldness index (C_I), and Xu Wenduo's humidity index (H_I) were adopted to simulate and predict the dynamics of the vegetation eco-boundary under climate warming in Northeast China. The future vegetation eco-boundary alteration types of zonal climax vegetation could be divided into three types, such as extended vegetation eco-boundary species (W_I value range for 45-95 °C • month) which would move northwards under climate warming, retreated vegetation eco-boundary species (W_I value range for 25-65 °C • month) which would retreat from the present localities, and extinct population species (W_I value range for 5-35 °C • month) which would be extinguished because the ecosystems they depend on disappeared. In Northeast China, there were differences for 15° latitudinal and 2 600 m altitudinal. Based on our research results, the edificators would move northwards about 400-700 km, steppe vegetation would move eastwards 900 km, and the populations would move upwards about 260-360 m in mountains if the global temperature increases 2 °C in the future. However, the moving distance would become shorter and shorter as the latitude and altitude increased. Therefore, the populations in alpine tundra zone at Daxing'an Mountains and Changbai Mountain might disappear. The results were expected to supply reference to local government when they set down strategies to respond to climate change in the future.
Key words: Warmth index; Humidity index; Vegetation; Eco-boundary
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Introduction

Climate warming is one of the most serious environment problems. It is sure that the present elevation of CO_2 and other greenhouse gases such as CH_4, N_2O, O_3 induced by human activities were making global climate to go through inexperienced changes (Zhao *et al.* 1998; Wu 1989). The ecosystems distributed in high latitude area were likely to experience much bigger change according to some previous researches (Sherwood 1983). This is the main reason that we focus on effects of possible climate change on the dynamics of the vegetation types eco-boundaries in Northeast China. There are two reasons to investigate the impact of climatic change in this region. Firstly, vegetation types in Northeast China have been protected comparatively perfectly for exploitation later and Northeast China has been being the largest timber source in China since the beginning of this century so that any correct prediction may be beneficial to Chinese economy (Zou *et al.* 1999). Secondly, very large amount of natural forests, steppes, and less-disturbed forests are still occurring across the whole region (Xu 1986). Vegetation eco-boundary or interface among three or more typical vegetation types, which is called ecotone was very sensitive to climate change, so it would change actively (Dyer *et al.* 1997; Mauchamp *et al.* 1993).

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Biography: *ZOU Chun-jing (1968-), male, Ph. doctor, associate researcher fellow in Laboratory of Ecological Process of Trace Substance in Terrestrial Ecosystem, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110015, P.R. China.
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Study area and methods

Study area

The study area is located at Northeast China. It was generally divided into three zones of forests and two types of steppes (temperate meadow steppe and temperate typical steppe) based on climate zone and dominant tree or herb species. Firstly, warm temper-

ate deciduous broad-leaved forest occurred in southwest corner of the research region, in which original vegetation has been disappeared because of human activities. Dominant tree species were *Quercus* spp and some pine (*Pinus* spp). Secondly, temperate broad-leaved and coniferous mixed forest can be seen in the areas of latitude 41°-50°N, where Korean pine (*Pinus koraiensis*) is dominant tree species mixed by many broad-leaved tree species, such as *Tilia* spp, *Quercus* spp, *Ulmus* spp, *Betula* spp, *Populus* spp, *Fraxinus* spp, *Acer* spp, and so on. At some sites, some coniferous trees, for example, firs (*Abies* spp) and spruces (*Picea* spp), were also companion tree species. Thirdly, cool temperate coniferous forest occurred on far northern part of the research area, in which frequent spring drought and cool climate made larch (*Larix gemilini*) to be dominant tree species mixed by birches, aspens and Mongolia pine (*Pinus sylvestris* var. *mongolica*). Fire ecology maintains the long-term stability of this type forest. At most case about 90% composition of forest community was larch (*Larix* spp), and forest biomass was 115-285 t/hm^2 (Feng 1989). Fourthly, temperate meadow steppe was in ecotone between forest zone and typical steppe zone, and it was dominated by *Stipa baicalensis, Filifolium sibiricum,* and so on. It was transitional vegetation type. Fifthly, temperate typical steppe locates at the western zone of study area. The main edificator of this kind vegetation was *Stipa grandis* and other species.

Study methods

Based on the prediction of General Circulation Models (GCMs) of the Earth's climate system, by the middle of next century, the concentration of CO_2 in atmosphere will be doubled and the global temperature will increase by 2 °C. We studied the law of zonal vegetation alteration under this condition in Northeast China in this paper. Considering the feature and distribution of natural vegetation in Northeast China (Xu 1985), our research focused on the three types of forests mentioned and other vegetation types, such as steppe, alpine tundra, *Larix* spp forest, and so on.

Climatic condition of each study site was estimated from the meteorological records of the nearest meteorological station using the records of 210 meteorological stations in Northeast China (1973-1987). If observation records during the periods were not available from the nearest meteorological station of the study site, the mean monthly temperature at the station was corrected using the records of the another close station which had complete records (Kim *et al.* 1977; Xu 1992).

Kira's warmth index (W_I) and coldness index (C_I) for a given altitude of a study site were calculated by the following equations using the mean monthly temperature (t_i) of the altitude estimated from the decreasing rates.

$$W_I = \sum_{i=1}^{12} (t_i - 5) \qquad (1)$$

The summation was made for months in which t>5 °C.

$$C_I = \sum_{i=1}^{12} (5 - t_i) \qquad (2)$$

The summation was made for months; where: t<5 °C.

Xu Wenduo proposed the humidity index (H_I) (Xu 1993) according to Kira's warmth index (W_I) and annual precipitation (P) of study site.

$$H_I = P / W_I \qquad (3)$$

Warmth index (W_I) is a kind of remainder index with 5 °C as the threshold temperature for plant growth, and coldness index (C_I) expresses the degree of coldness during the non-vegetative period. Humidity index (H_I) expresses the degree of moisture during the growth period, and it was extensively applied to research on relationship between vegetation and local climate.

Results and analyses

Impact of climate warming on zonal edificators in Northeast China

Moisture conditions, temperature conditions, and their assemble are limiting factors to vegetation distribution. Transform of moisture-temperature conditions led by global climate change must influence the eco-geographic distribution of zonal vegetation edificators. The change of edificators will lead to variation of vegetation eco-boundary.

We calculated the moisture-temperature indexes of 34 main edificators in Northeast China based on Kira's warmth index (W_I), coldness index (C_I) and Xu Wenduo's humidity index (H_I) mentioned above by using vegetation samples.

To avoid misinterpretation, we adopted lower limit and upper limit value of moisture-temperature indexes to predict the alteration situation of zonal vegetation eco-boundary dominated by zonal edificator species. Table 1 was prepared to show whether there were any appreciable groups of species having similar ranges of thermal distribution. In the Table 1, 34 species were grouped according to the combina-

tion of their lower limit (upper limit of altitudinal distribution) and upper limit (lower limit of altitudinal distribution) of optimal thermal distribution. We divided the future population types of 34 main edificators (most of them are tree species) into three groups (Xu *et al.* 1998).

The thermal range of individual species in fact changed gradually and continuously. However, the species were not distributed homogeneously in the Table 1, but tended to form groups. Some groups were quite discrete, while others were less defined. The following three groups might be distinguished as marked by bold lines in the Table 1.

First of all, extended vegetation eco-boundary species (W_I value range: 45-95 °C • month), the extended population preferred to warmth and it could be grouped into two groups according to its W_I value as follows: (1) W_I value being 45-75 °C • month. This group included many tree species, such as *Pinus koraiensis, Abies holophylla, Taxus cuspidata, Quercus mongolica, Phellodendron amurense, Acer triflorum , Acer mandshurica*, and so on; (2) W_I value being 55-95 (°C • month). It included *Pinus tabulaeformis, Pinus densiflora, Quercus liaotungensis, Quercus variabilis* and some subtropical species, for example, *Rhus verniciflua, Rhus chinensis, Linderaa obtusiloba, Magnolia parviflora,* etc. These populations needed higher temperature condition, so they would move northwards gradually during the climate warming in the future. Actually, some temperate and warm-temperate species were found in Daxing'an Mountains in recent years, for example, *Fraxinus mandshurica, Phellodendron amurense,* and some *Ulmus* spp were found at Huma River watershed, Pangu River watershed, and Shibazhan District in Heilongjiang Province. *Tilia amurensis* distributed at Dayangshu District, *Schizandra chinensis, Lonicera maachii*, and so on, distributed at Gan River watershed. Age of these plants was below 50 years old, no elder, which proved that they moved from southern area after the beginning of this century.

Table 1. The future alteration types of distribution of edificators of zonal vegetation in Northeast China

Lower limit (warmth index)/ (°C • month)	Upper limit (warmth index)/ (°C • month) 15-24	25-34	35-44	45-54	55-64	65-74	75-84	85-94	Total species
14-5	31 32								
	33 34								4
24-15		3 13							2
34-25				4 6 10	7 8				5
					9 16				3
44-35					17				
					1 15	11 12			
54-45						14 18			
						19 20			
					27 28	21 29			12
								22 25	
64-55								30	3
74-65								5 24	2
84-75								2 23 26	3
Total species	4	2		3	9	8		8	34

Second, retreated vegetation eco-boundary species (W_I value range for 25-65 °C • month), these species belongs to Sibirica components, and they were the immigrant species during the last Glacial Epoch of Quaternary Period. The group included *Larix dahurica, Picea koyamai* var. *koraiensis, Picea jozoensis, Abies nephrolepis, Pinus sylvestris* var. *mongolica*, and so forth. They would retreat northwards under climate warming because they came from northern area. In Daxing'an Mountains, these species retreated because of climate warming, for example, *Larix dahurica* once moved southwards the area (nearly 43° N). However, it distributed only at A'er Mountains and its adjacent area, which showed that *Larix dahurica* had retreated. Moreover, *Larix dahurica* distributed with exist of permanent frozen soil, and it retreated due to melting of permanent frozen soil. According to research and survey on frozen soil in Amuer district in northern area of Daxing'an Mountains (Table 2) (Tan *et al.* 1995), the frozen soil was decreasing with climate warming, and then the eco-boundary of *Larix dahurica* forest was moving northwards gradually.

Third, extinct population species (W_I value range

for 5-35 °C • month), the group included *Dryas tschonoskii, Phyllodoce caerulea, Artous japonica, Empertrum sibiricum, Polygonatum ajanense, Arctous alpinus*, which originated from Arctic, and they belonged to Arctic-Alpine elements. Their distribution in Northeast China resulted from alternative cold and warm effects during Glaciation and Interglaciation. During Glacial Epoch, these Arctic species spread all over Northeast China due to climate cooling. But, during Interglacial Epoch, these species moved northwards or upwards high mountains. With the climate changes in the future, the alpine vegetation in Daxing'an Mountains, Xiaoxing'an Mountains and Changbai Mountain would be extinct because of no ecological conditions similar to Arctic area.

Table 2. Comparison of frozen soil during different period in Amuer district of Heilongjiang Province

Survey time (year)	Annual mean temperature /°C	Depth of frozen soil /cm
1975	-3.7	107.5
1978-1979	-4.2	120.0
1978-1979	-1.9	62.0
1978-1978	-2.8	85.4
1991-1992	-2.1	67.5
1991-1992	-2.0	65.0

Dynamics of the eco-boundary of zonal edificators under climate warming

In Northeast China, there are 15 ° latitudinal differences and 2 600 m altitudinal differences. These differences result in complexity of plant population. From south to north in Northeast China, there appear in turn warm-temperate populations, temperate populations, and cold-temperate populations. There exists a linear relationship between warmth index (W_I) and latitude (X), longitude (Y) and altitude (H) as follows:

$$W_I = 288.94 - 2.51X - 0.81Y - 0.038H(r = 0.9812) \quad (4)$$

This model reflected macroscopic distribution pattern and law of warmth index value in plant growth season in the mountains in Northeast China. The law was that, moving northwards 1° latitude, W_I value decreased 2.51 (°C • month); moving eastwards 1° longitude, W_I value decreased 0.81 (°C • month); and moving upwards 100 m, W_I value decreased 3.8 (°C • month). Based on the equation, it was calculated that the edificators would move northwards about 400-700 km and steppe vegetation would move eastwards 900 km when the global temperature increased 2 °C (Table 3). However, the moving distance would become shorter and shorter as the latitude increased. According to the results of calculation, the populations would move upwards to about 260-365 m if the temperature increased 2 °C, but the moving distance would be nearer and nearer as the altitude increased. Therefore, the populations in alpine tundra zone at Daxing'an Mountains and Changbai Mountain might disappear.

Table 3 showed that vertical thermal index value of a certain population was lower than that of horizontal, because altitudinal decrease rate of temperature was one thousand times of that of latitudinal decrease rate, which was one of the main reasons for rapid extinguish of alpine plant species.

Impact of climate warming on distribution of vegetation types

The horizontal changes of vegetation zone distribution

The horizontal vegetation zonation includes latitudinal zonation and longitudinal zonation. Vegetation of any certain locality reflects the latitudinal and longitudinal zonation. Based on the above regulation, we carried on analysis of Principal Components Analysis (PCA) on 210×7 data matrix, and 7 factors are: F_1 (latitude), F_2 (longitude), F_3 (altitude), F_4 (precipitation), F_5 (W_I), F_6 (C_I) and F_7 (H_I) of 210 meteorological stations in Northeast China. The results are as follows (Table 4).

Table 4 showed the first 2 components (F_I, F_2) accounted for 77.684% of variation, so we could be divided the vegetation into seven groups (Table 5).

Generally speaking, zonal vegetation types came into being and developed under zonal climatic conditions. Based on viewpoint of Dynamic Geobotany, there must be certain zonal climax vegetation type under certain climate. Moreover, in one certain climate zone, there was only zonal climax vegetation. So, the data reflected the climate characters and certain ecogeographic patterns of different vegetation types. With climate warming in the future, zonal climax vegetation in Northeast China would move northwards about 400-700 km besides the change of composition and structure.

Furthermore, in plain vegetation types, there was a close linear relationship among warmth index (W_I), latitude (X), longitude (Y), and altitude (H) as follows:

$$W_I = 343.96 - 2.73X - 1.16Y - 0.027H(r = 0.9137) \quad (5)$$

The model showed that, moving northwards 1° latitude, W_I value decreased 2.73 (°C •month); moving eastwards 1° longitude, W_I value decreased 1.16 (°C • month); and moving upwards 100 m, W_I value decreased 2.7 (°C • month). Therefore the steppe vegetation would move eastwards more than 900 km

with the future climate warming.

As far as the moving distance was concerned only, steppe vegetation moved faster than forest vegetation. However, vegetation distribution was controlled by many ecological factors, such as temperature, precipitation, soil conditions and so on. So steppe vegetation would not move far as theoretical expectation.

Table 3. The future eco-boundary of the zonal vegetation in northeast China

Species	Limit	Samples	W_I /(°C • month)			C_I /(°C • month)			T /°C		H_I /mm • (°C • month)$^{-1}$		Moving distance /km
			Mean	SD	SD/7	Mean	SD	SD/5	Mean	SD	Mean	SD	
Pinus	Upper	8	33.1	5.7	0.8	-120.2	13.8	2.7	-1.6	1.2	-	-	260
koraiensis	Northern	3	45.7	3.2	0.5	-125.9	5.6	1.1	-0.7	0.8	10.5	1.3	443
Tilia	Upper	3	31.6	3.5	0.5	-114.5	7.5	1.5	-1.7	1.2	-	-	260
amurensis	Northern	3	36.2	7.0	1.0	-128.6	9.0	1.8	-1.5	1.0	10.7	1.7	443
Acer mono	Upper	7	43.3	6.4	0.9	-199.1	10.9	2.2	0.1	1.0	-	-	260
	Northern	3	45.7	7.0	1.0	-129.1	8.8	1.8	0.7	0.8	10.1	1.0	443
Acer	Upper	5	31.0	7.3	1.0	-11.5	8.6	1.7	-0.5	1.0	-	-	260
tagmentosum	Northern	3	47.7	7.8	1.1	-129.6	6.8	1.4	-1.2	0.2	10.5	1.3	443
Acer	Upper	7	40.8	6.5	0.9	-102.3	8.9	1.8	0.5	0.6	-	-	260
ukurunduense	Northern	2	46.0	9.8	1.4	-132.0	7.4	1.5	-1.6	0.0	10.5	1.3	443
Abies	Upper	9	44.4	3.6	0.5	-97.7	8.9	1.8	0.7	0.9	-	-	260
holophylla	Northern	9	62.8	4.7	0.7	-83.5	6.9	1.4	3.2	0.8	12.0	2.0	620
Carpinus	Upper	10	51.4	5.9	0.8	-91.5	8.6	1.7	1.6	1.0	-	-	313
cordata	Northern	6	61.5	6.3	0.9	-85.2	10.3	2.1	2.9	1.2	9.8	1.3	620
Abies	Upper	8	49.1	5.7	0.8	-92.1	7.4	1.5	4.3	0.7	9.8	1.3	260
triflorum	Northern	3	71.0	6.9	1.0	-77.3	7.4	1.5	4.3	0.7	9.8	1.3	620
Abies	Upper	10	51.4	5.4	0.8	-91.2	8.2	1.6	2.0	0.7	-	-	313
mandshurica	Northern	4	70.0	7.9	1.1	-77.3	7.3	1.5	3.6	1.1	9.8	1.3	620
Pinus	Upper	8	61.4	4.4	0.6	-78.7	7.2	1.4	3.4	0.8	-	-	365
tabulaeformis	Northern	12	79.3	4.2	0.6	-60.8	4.9	1.0	6.5	0.7	7.8	2.6	620
Pinus	Upper	3	73.1	4.9	0.7	-47.7	8.9	1.8	7.1	14	-	-	365
densiflora	Northern	5	88.1	3.3	0.5	-33.7	7.0	1.4	9.1	0.9	12.4	1.9	620
Picea	Upper	4	45.0	2.7	0.4	-98.0	2.4	0.5	0.9	0.6	-	-	365
meyeri	Northern	2	51.0	2.8	0.4	-88.0	2.8	0.6	1.8	0.6	7.6	1.1	708
Quercus	Upper	5	62.0	8.3	1.2	-80.6	4.9	1.0	3.6	0.9	-	-	260
liaotungensis	Northern	3	70.0	10.0	1.4	-70.0	6.1	1.2	5.2	1.0	11.8	0.9	620
Quercus	Upper	4	71.5	6.6	0.9	-64.7	3.7	0.7	5.4	1.1	-	-	365
acutissima	Northern	4	80.0	7.1	1.0	-56.5	3.5	0.7	6.7	0.8	-	-	365
Quercus	Upper	5	76.2	2.5	0.4	-51.0	7.9	1.6	7.1	0.8	-	-	365
variabilis	Northern	5	83.2	2.2	0.3	-43.6	7.3	1.5	8.4	0.7	9.9	2.8	620
Stipa	Western	4	64.6	4.7	0.7	-98.2	9.4	1.9	2.4	1.1	7.5	0.2	926
baicalensis	Northern	3	80.4	2.2	0.3	-66.0	7.2	1.4	6.1	0.8	5.2	0.2	-
Stipa	Western	3	73.0	1.4	0.2	-82.8	2.3	0.5	4.2	0.3	5.7	0.7	926
grandis	Northern	4	79.4	8.5	1.2	-66.3	5.8	1.2	5.9	0.8	4.2	0.4	-
Stipa	Western	3	78.8	1.0	0.1	-68.1	1.4	0.3	5.8	0.2	5.0	0.7	926
krylovii	Northern	4	68.4	10.4	1.5	-74.7	27.3	5.5	4.2	2.8	4.8	0.5	-
Stipa	Western	3	86.9	5.0	0.7	-52.7	3.2	0.6	7.9	0.5	7.5	0.4	926
bungeana	Northern	3	82.1	9.4	1.3	-54.1	8.0	1.6	7.3	1.4	5.8	1.1	-

Notes: W_I --warmth index, C_I --coldness index, H_I -humidity index, T -monthly temperature.

Table 4. Eigenvalues and percentage of total variation

	Principal components						
	F_1	F_2	F_3	F_4	F_5	F_6	F_7
Eigenvalue	3.331	2.107	1.106	0.370	0.042	0.025	0.019
Contribution rate	47.580	30.104	15.799	5.292	0.598	0.360	0.267
Accumulated contribution rate (%)	47.580	77.684	93.483	98.775	99.373	99.733	100.000

Notes: F_1 --latitude, F_2 --longitude, F_3 --altitude, F_4 --precipitation, F_5 --W_I, F_6 --C_I and F_7 --H_I of 210 meteorological stations in Northeast China.

The vertical changes of vegetation zone distribution

We divided Northeast China into three natural areas according to the vegetation horizontal zonation rule and geographic characters and discussed influence of climate warming on them respectively.

First of all, in temperate mixed coniferous broad-leaved forest zone, the region located at eastern mountains of Northeast China, which included Xiaoxing'an Mountains, Wanda Mountains, Zhangguangcai Mountains, Changbai Mountain, and Liaodong Mountains. If the future temperature increases 2 °C, the vertical changes of vegetation zones would occur. For example, in the Changbai Mountain, mixed *Abies holophylla--Pinus koraiensis* broad-leaved forest (W_I>65 °C • month) would move from 700 m to 963 m along altitude; mixed *Pinus koraiensis* broad-leaved forest (W_I is 65-50 °C •month) would move from 700-1 100 m to 963-1 363 m; Dark coniferous forest (*Picea-Abies* forest) zone (W_I is 50-23 °C • month) would move from 1 100-1 800 m to 1 363-2 063 m; Subalpine forest (*Betula ermanii* forest) zone (W_I is 23-15 °C • month) would move from 1 800-2 000 m to 2 063-2 158 m; and alpine tundra zone (W_I <15 °C •month) would move from 2 000 m to 2 158 m and above area.

Table 5. Moving state of zonal vegetation types in Northeast China

Zonal climax vegetation types	Samples	Thermal indexes /(°C • month)			Moving
		Optimal range	W_I	C_I	distance /km
Cold-temperate bright coniferous forest	11	33.0-50.2	41.6±7.3	-138.1±116.8	443
Temperate mixed *Pinus koraiensis* broad-leaved forest	38	58.1-66.9	62.5±3.7	-91.6±8.1	531
Temperate mixed *Abies holophylla-Pinus koraiensis* broad-leaved forest	20	61.3-74.3	67.8±5.5	-74.6±5.7	620
Warm-temperate mixed *Pinus tabulaeformis-Quercus* spp forest	16	86.3-90.5	88.4±1.8	-47.8±3.6	708
Warm-temperate mixed *Pinus densiflora-Quercus* spp forest	7	85.9-92.5	89.2±2.8	-33.9±5.1	708
Temperate meadow steppe	30	62.7-76.5	69.6±5.8	-84.9±11.1	926
Temperate typical steppe	24	73.7-80.3	77.0±2.8	-67.4±3.9	926

Notes: W_I --warmth index, C_I --coldness index.

Second, in cold-temperate coniferous forest area, the region located in mountains of northern Daxing'an Mountains, from Heilongjiang River watershed nearby Mohe, Heilongjiang Province to Taoer River of Jilin Province. With the climate warming, the vertical distribution of vegetation zones would change. For example, in Baihali Mountains (its altitude is 1 410 m), *Quercus mongolica--Larix dahurica* forest (W_I>50 °C •month) would move from 450 m to 686 m; *Larix dahurica* and *Pinus sylvestris* var. *mongolica* bright coniferous forest zone (W_I is 50-25 °C • month) would move from 450-1 100 m to 686-1363 m; *Pinus pumila--Betula ermanii* forest zone (W_I is 25-15 °C • month) would move from 1 100-1 400 m to 1 363-1 410 m; and the alpine tundra would be disappear.

Third, in temperate steppe zone, we chose Huanggangliang Mountains (its altitude is 2 029 m) which is highest peak of Daxing'an Mountains to show the vertical vegetation distribution as follows: *Stipa baicalensis--Filifolium sibiricum* meadow (W_I is 45 °C • month, H_I is 7.5 mm/(°C • month) would move from 1 300 m to 1 563 m; mixed coniferous broad-leaved forest zone (W_I is 45-30 °C • month), H_I is 9.5-18 mm/(°C • month) would move from 1 300-1 700 m to 1 563-1 963 m, and coniferous forest zone and alpine meadow would disappear.

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